Markov blankets are general physical interaction surfaces
Comment on
"Morphogenesis as Bayesian inference: A variational approach to pattern formation and control in complex biological systems" by Michael Levin et al.

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Kuchling, Friston, Georgiev and Levin ([1]; hereafter KFGL) show how to construct, starting from generic classical physical assumptions, a model of a cell, or of any biological system, as an inferential agent that acts to minimize Bayesian surprise. Key to this construction is the concept of a Markov blanket, defined in KFGL, §2.2.3 as the Cartesian product of the sets of "sensory" and "active" states of the cell / system. The existence of the Markov blanket assures the conditional independence of "external" and "internal" states that is required if the probabilities of external and internal states used in Bayes' theorem are to be well-defined. As KFGL note, "Most fundamentally, we have assumed the existence of a

Markov blanket, which separates external and internal states through a set of active and sensory states ... it needs to be verified empirically that signal transmission and adaptive responses on a cellular level are not instantaneous (as in our adiabatic approximations), and that active states indeed cause changes in sensory states" (p. 18).

Here we show that when KFGL's classical physical assumptions are replaced by generic quantum-theoretic assumptions, including consistency with Special Relativity, both the existence of Markov blankets and the non-instantaneous nature of responses naturally result. These results hold for *any* physical system embedded in and interacting with an environment, provided only that information is conserved. Hence KFGL's construction of Bayesian inference applies, in principle, to any physical system. We argue that this is not surprising, but rather is to be expected on the basis of principles as diverse as the Holographic principle [2], Deutsch's "physical" statement of the Church-Turing thesis [3], and the commonplace assumption that any physical system can be considered an observer (e.g. [4]).

Consider any closed physical system X with an associated complex Hilbert state space $\mathcal{H}_X$, and consider an arbitrary decomposition $X = AB$ with associated state space decomposition $\mathcal{H}_X = \mathcal{H}_A \otimes \mathcal{H}_B$. Let H_X be the Hamiltonian self-interaction of X; hence the time propagator $\mathcal{P}_X(t) = exp((-\imath/\hbar)H_X t)$. We assume that H_X is local. With the decomposition $X = AB$, we have $H_X = H_A + H_B + H_{AB}$, where H_{AB} represents the $A - B$ interaction and all interactions are local. Here A and B are open systems; B can be considered the "environment" of A and vice-versa.

There is a natural sense in which the states and dynamics of A and B are "hidden" from each other in any such decomposition. The tensor product $\otimes$ is associative and the Hamiltonian H is additive, so we can choose an arbitrary decomposition $B = CD$ and write $\mathcal{H}_B = \mathcal{H}_C \otimes \mathcal{H}_D$ and the interaction $H_B = H_C + H_D + H_{CD}$ without affecting the values of H_X, H_A, or H_{AB} in any way. Hence the $A - B$ interaction is fully independent of the internal structure of B and of any interactions between internal components of B; similarly it is fully independent of any internal structure or interactions of A. We can formulate this independence in informational terms by saying: the interaction H_{AB} *carries no information* about the internal structures or dynamics of either A or B across the $A - B$ boundary. The conditional independence of A and B provided by a Markov blanket thus follows, in the current framework, from the locality of H_X and the decompositional structure of the state space.

What, then, *does* the interaction H_{AB} carry information about? The only remaining possibility is that H_{AB} carries information about *itself*, i.e. about the relationship between A and B. This is what a Markov blanket does. Hence we appear to have the function of a Markov blanket "for free" when we make only generic quantum-theoretic assumptions.

To make this precise, we have to say what "information" means. The formal description given so far is entirely quantum-kinematical; no classical states or dynamics have yet been characterized. The idea of a signal or interaction "carrying information" is, however, a classical idea: it refers to the transfer of classical information. This is, moreover, the sense of information relevant to KFLG's construction of Bayesian inference. Where does this classical information come from?

The question of the origin of classical information is one version of the notorious "measurement problem" in quantum theory [4, 5]. Here we will sidestep all philosophical discussions of interpretation, and ask merely what classical information is available to be characterized. The answer to this more practical question is clear and uncontroversial: the available classical information is the set of real eigenvalues of H_{AB}. These eigenvalues, when considered together, fully specify H_{AB}; hence they provide all the information about the relationship between A and B that there is to be had. We can consider this information to flow from B to A, choose an orthonormal basis, and write H_{AB} as:

$$H_{AB} = \beta^A k_B T^A \sum_i \alpha_i^A M_i^A, \tag{1}$$

where the M_i^A are orthogonal Hermitian operators with binary eigenvalues, the $\alpha_i^A \in [0, 1]$ are such that $\sum_i \alpha_i^A = 1$, k_B is Boltzmann's constant, T^A is A's temperature, and $\beta^A \geq 1$ is a measure of A's thermodynamic efficiency that depends on the "hidden" dynamics H_A. Here we make the now-standard assumption of a finite, discrete interaction, which is justified below. The M_i^A are traditionally called "measurement" operators, and correspond to binary-valued "questions to Nature" [6] posed by A to its environment B. The idea of "answering" a question is classical, and implies an irreversible state change [7]: each question from A that B "answers" transfers one bit from B to A and is paid for by the transfer of $\beta^A k_B T^A$ from A to B. The action to transfer N^A bits from B to A in time Δt is:

$$\int_{\Delta t} dt \mathcal{P}_X(t) = N^A \beta^A k_B T^A \Delta t \tag{2}$$

in units of $\hbar$, confirming that heat is dissipated by A, i.e. transferred from A to B by H_{AB}. Clearly the same expressions can be employed to represent information transfer from A to B by replacing "A" by "B" as a superscript and summing over an index j. Within the interval Δt, therefore,

$$N^A \beta^A T^A = N^B \beta^B T^B, \tag{3}$$

so the *recorded* information asymmetry is proportional to the thermal asymmetry:

$$N^A / N^B = \beta^B T^B / \beta^A T^A. \tag{4}$$

Setting $T^A = T^B$ for simplicity, the asymmetry in recorded classical information, i.e. *memory* for what is observed depends on the thermodynamic efficiencies and hence the internal dynamics H_A and H_B.

The classical idea of "dissipation" is, at time scales larger that Δt, observer-dependent [8]; A and B each "see" the other's thermodynamic entropy increase as the other "loses" information in compliance with the Second Law. However, the von Neumann entropy of the combined system X remains constant at zero as required by the conservation of information. As X is closed, this latter statement is merely definitional; the total von Neumann entropy cannot be observed.

The $A - B$ interaction defined by (1) can be realized in a simple physical model. Letting N be the number of operators M_i^A (or M_j^B) and hence the maximal number of bits transferrable by H_{AB}, consider a lattice of N causally-independent qubits, and let the M_i^A and M_j^B be z-spin operators that each act, in alternation, on one of these qubits. The observed states of B for A are $\psi^B(t) = \otimes|i\rangle$ and of A for B are $\psi^A(t + \delta t) = \otimes|j\rangle$, where the time t is discrete and δt is the delay between A's and B's observations. The extents to which A and B can record observations of these states depend on β^A and β^B respectively. We can regard this qubit lattice as the data register of a quantum computer controlled by the propagator $\mathcal{P}_X(t)$; this representation is universal for finite-dimensional systems [3, 9]. The lattice states provide, in this representation, a natural "encoding" of the eigenvalues of H_{AB}.

Nothing has been said, thus far, about geometry. Any physical interaction can, however, be regarded as ocurring on a holographic screen, with an area of at least $4l_P^2$, with l_P the Planck length, associated with each encoded bit [2, 10]. For instance, within the semi-classical limit of the Euclidean picture of space-time [11], we might argue that $\mathcal{S}^2 \times \mathcal{S}^2$ topological configurations capture information at mesoscopic scales larger than l_P and thus realize holographic encoding. In any such model, the assumption of finite, discrete eigenvalues for H_{AB} corresponds to the assumption of a finite screen, i.e. a finite spatial boundary between A and B. As H_{AB} and hence H_X do not depend on the spatial variables on the screen, they are ancillary, and can be considered to define the boundary of B from A's perspective or vice-versa.

We now have all the ingredients of a classical Markov blanket: a spatial boundary with a defined, discrete bidirectional information flow that assures conditional independence of the systems it separates. Information is "displayed" on this boundary for both A and B to "see," but their ability to record this information for future use is detemined by their mutually-unobservable internal dynamics. The information that each system records, at each time step, is its current representation of the state of the other system; no other state information is available.

The variational free energy of B is minimized for A, in this model, when the internal dynamics H_A is a good predictor of the observable effects of H_B. In this case A is a "model" of B in the sense of the Good Regulator Theorem [12].

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

[1] F. Kuchling, K. Friston, G. Georgiev and M. Levin, "Morphogenesis as Bayesian inference: A variational approach to pattern formation and control in complex biological systems," *Physics of Life Reviews*, this issue.

[2] R. Bousso, "The holographic principle," *Reviews of Modern Physics*, vol. 74, no. 3, pp. 825–874 (2002).

[3] D. Deutsch, "Quantum theory, the Church-Turing principle and the universal quantum computer," *Proceedings of the Royal Society of London A*, vol. 400, pp. 97–117 (1985).

[4] M. Schlosshauer, *Decoherence and the Quantum-to-Classical Transition*, Springer, 2007.

[5] A. Cabello, "Interpretations of quantum theory: A map of madness," Preprint arXiv:1509.04711v1, 2015.

[6] J. A. Wheeler, "Law without law," in *Quantum Theory and Measurement*, J. A. Wheeler and W. H. Zurek, Eds., pp. 182–213, Princeton University Press, 1983.

[7] R. Landauer, "Irreversibility and heat generation in the computing process," *IBM Journal of Research and Development* vol. 5, pp. 183–195 (1961).

[8] M. Tegmark, "How unitary cosmology generalizes thermodynamics and solves the inflationary entropy problem," *Physical Review D* vol. 85, art. 123517 (2012).

[9] S. Lloyd, "Universal quantum simulators," *Science* vol. 273, no. 5278, pp. 1073–1078 (1996).

[10] E. Verlinde, "On the origin of gravity and the laws of Newton," *Journal of High-Energy Physics* vol. 2011, art. 29 (2011).

[11] S. W. Hawking, D. N. Page and C. N. Pope, "Propagation of particles in spacetime foam," *Physics Letters* vol. 86B, no. 2, 175–178 (1979).

[12] R. C. Conant and W. R. Ashby, "Every good regulator of a system must be a model of that system," *International Journal of System Science* vol. 1, no. 2, pp. 89–97 (1970).